Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

AD-A278 753

REPORT DOCUME

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Final Report Project 521646	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 94 0251
6a. NAME OF PERFORMING ORGANIZATION University of Connecticut ESE Department 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR, Optimization & Discr. Math
6c. ADDRESS (City, State, and ZIP Code) ESE Department, U-157 260 Glenbrook Rd. Storrs, CT 06269-3157	7b. ADDRESS (City, State, and ZIP Code) Bolling AFB, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUM F49620-93-1-0164P00001
8c. ADDRESS (City, State, and ZIP Code) Bolling AFB, DC 20332-6448	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

94-12971

12pg

DTIC ELECTE MAY 02 1994 S G D

11. TITLE (Include Security Classification)
Estimation with Multisensor/Multiscan Detection Fusion (U)

12. PERSONAL AUTHOR(S)
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13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 3/1/93 to 3/1/94	94-03-04	11

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Tracking, Assignment, Control

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

In this report we deal with the following topics:
Data Association for Heterogeneous Sensors
Efficient L-D Factorization Methods for PDA, IMM and IMMPDA Filters
Tracking with Debiased Consistent Cbnverted Measurements
Stabilization of Jump Linear Gaussian Systems
Ballistic Missile Track Initiation from Satellite Observations
Beam Pointing Control of a Monopulse Radar for Maneuvering Target Tracking
Target Tracking with Glint Noise
Image Segmentation Based on Optimal Layering for Precision Tracking
Performability Studies of AMSs with Multiple Part Types
Markov-Reward Models and Hyperbolic Systems
Estimation and Tracking: Principles, Techniques, and Software

DTIC QUALITY INSPECTED 3

94 4 28 083

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	
22a. NAME OF RESPONSIBLE INDIVIDUAL Y. Bar-Shalom	22b TELEPHONE (Include Area Code) 203-486-4823 / 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 — Previous editions are obsolete — SECURITY CLASSIFICATION OF THIS PAGE

94 4 28 083

0. INTRODUCTION

This report summarizes the results obtained during the period 3/1/93 - 3/1/94 of the Grant. The topics are divided according to the publications generated from the research effort.

Section 1 describes our work on discrete optimization - an S-dimensional assignment algorithm.

Section 2 deals with new factorization algorithms for accurate numerical performance for several state estimators.

Section 3 presents an accurate numerical technique for coordinate conversion in target tracking.

Sections 4 and 5 deal with stochastic control and stabilization of hybrid systems (with continuous and discrete uncertainties).

Section 6 deals with numerical search techniques for ill-conditioned optimization problems with application to ballistic missile trajectory estimation.

Section 7 deals with the control of a phased array radar when tracking a highly maneuvering aircraft.

Section 8 presents an algorithm for handling the glint phenomenon when tracking a target.

Section 9 describes an optimized image processor/tracker for a target with an IR camera when the background can be stronger or weaker than the target.

Sections 10 and 11 describe performability studies for automated manufacturing systems (AMS) that characterize the performance of a discrete-event system in the presence of failures and repairs.

Section 12 presents a brief description of a textbook just published by one of the Co-PIs of this project.

1. A MULTISENSOR-MULTITARGET DATA ASSOCIATION ALGORITHM FOR HETEROGENEROUS SENSORS

(Somnath Deb, Krishna R. Pattipati, and Yaakov Bar-Shalom, IEEE Transactions on Aerospace and Electronics Systems, April 1993)

The problem dealt with here is one of associating data from three spatially distributed heterogeneous sensors, each with a set of detections at the same time. The sensors could be active (three-dimensional or two-dimensional radars), or passive (electro-optical sensors measuring the azimuth and elevation angles of the source). The source of a detection can be either a real target, in which case

the measurement is the true observation variable of the target plus measurement noise, or a spurious one, i.e., a false alarm. In addition, the sensors may have nonunity detection probabilities. The problem is to associate the measurements from sensors to identify the real targets, and to obtain their position estimates. Mathematically, this (static) measurement-target association problem leads to a generalized 3-D assignment problem, which is known to be NP-hard.

2. EFFICIENT L-D FACTORIZATION ALGORITHMS FOR PDA, IMM, AND IMMPDA FILTERS

(Vijaya Raghavan, Krishna R. Pattipati, and Yaakov Bar-Shalom, IEEE Transactions on Aerospace and Electronic Systems, October 1993)

Over the past twenty years, square-root factorization methods for Kalman filtering have gained popularity due to increased numerical robustness and accuracy provided by these methods. However, square-root formulations have not been developed for the state-of-the-art tracking algorithms, such as the Probabilistic Data Association (PDA) - for tracking in clutter, Interacting Multiple Model (IMM) - for tracking maneuvering targets, and IMMPDA (for tracking maneuvering targets in clutter). The only exception is the recent square-root PDAF by Kenefic. In this paper, we show that there is a substantially better implementation of the square-root PDAF than Kenefic's algorithm in terms of both numerical robustness and computational efficiency. The computational savings of our algorithm are obtained by using successive L-D rank-one corrections instead of the Modified Weighted Gram-Schmidt (MWG-S) technique for the overall covariance update. For the covariance prediction step, we present an alternate implementation of the square-root version when the process noise covariance is time-invariant, that requires successive L-D

rank-one corrections obviating the need to use the computationally expensive MWG-S technique. On the average, the proposed algorithm for square-root PDAF requires half the number of computations required by Kenefic's algorithm. We extend the same approach to develop computationally efficient square-root algorithms for the IMM and IMMPDA filters.

3. TRACKING WITH CONSISTENT CONVERTED MEASUREMENTS VS. THE EKF
(Don Lerro and Yaakov Bar-Shalom, IEEE Transactions on Aerospace and Electronics Systems, July 1993)

In tracking applications target motion is usually best modeled in a simple fashion using Cartesian coordinates. However, in most systems the target position measurements are provided in terms of range and azimuth (bearing) with respect to the sensor location. This situation requires either converting the measurements to a Cartesian frame of reference and working directly on converted measurements or using an Extended Kalman Filter (EKF) in mixed coordinates. An accurate means of tracking with debiased consistent converted measurements is presented which accounts exactly for the sensor inaccuracies over all practical geometries and accuracies. This method is compared to the mixed coordinate EKF approach as well as the standard converted measurement approach which is an acceptable approximation only for moderate cross-range errors. This new approach is shown to be more accurate in terms of position and velocity errors and provides consistent estimates (i.e. compatible with the filter calculated covariances) for all practical situations. The combination of parameters (range, range accuracy, and azimuth accuracy) for which debiasing is needed is presented in explicit form.

4. STABILIZATION OF JUMP LINEAR GAUSSIAN SYSTEMS

(Guolin Pan and Yaakov Bar-Shalom, Proc. 32nd IEEE Conference on Decision and Control, December 1993)

The importance of jump linear (JL) systems in modeling practical physical systems, e.g., tracking, repairable systems, systems subject to abrupt changes etc., has drawn extensive attention. Results have been obtained in control, stabilization and filtering, when the mode (system model) is assumed to be directly and perfectly observable, which, in many applications, is an unrealistic assumption. When this is not the case, the optimal control and the stabilization problems become very difficult due to the dual effect. In this work, we assume that the mode is not observable, but the base state is perfectly measured. We give a sufficient condition to stabilize a JL system using an "i.i.d. controller" (a controller derived using an i.i.d. assumption for the system mode), a necessary condition of stabilizability and an upper and a lower bound to the optimal cost for a JL system. We show that a controller stabilizing the noise-free system also stabilizes the noisy one. An algorithm to compute the optimal feedback gain for a system with i.i.d. modes is presented and its convergence is proven.

5. NONLINEAR STABILIZATION OF JUMP LINEAR GAUSSIAN SYSTEMS

(Guolin Pan and Yaakov Bar-Shalom, Proc. 1994 American Control Conference)

The importance of jump linear (JL) systems in modeling practical physical systems, e.g., tracking, repairable systems, systems subject to abrupt changes etc., has drawn extensive attention. Results have been obtained in control, stabilization and filtering, when the mode

(system model) is assumed to be directly and perfectly observable, which, in many applications, is an unrealistic assumption. When this is not the case, the optimal control and the stabilization problems become nonlinear (dynamic) optimization problems and very difficult due to the dual effect. This work, under the assumption that the mode is not available, but the base state is perfectly measured, answers the following question positively: If the JL system is stabilizable by a linear feedback control, can one find a better stabilizing controller? Two such nonlinear control schemes are presented. For the case of an unknown parameter problem, an example is given to show that the cost from using a nonlinear stabilizing controller derived in this paper is within a few percent from a lower bound of the (unknown) optimal cost, and is about half of the cost by using an algorithm from the literature, due to Saridis.

6. BALLISTIC MISSILE TRACK INITIATION FROM SATELLITE OBSERVATIONS
(Murali Yeddanapudi, Yaakob Bar-Shalom, Krishna R. Pattipati and Somnath Deb, Proc. SPIE Conference, Signal & Data Processing of Small Targets, vol. 2235, April 1994)

This paper presents an algorithm to initiate tracks of a ballistic missile in the initial exoatmospheric phase, using line of sight measurements from one or more moving platforms (typically satellites). The major feature of this problem is the poor target motion observability which results in a very ill-conditioned estimation problem.

The Gauss-Newton iterative least squares minimization algorithm for estimating the state of a nonlinear deterministic system with nonblinear noisy measurements has been applied to the problem of

angles-only orbit determination using more than three observations. A major shortcoming of this approach is that convergence of the algorithm depends strongly on the initial guess. By using the more sophisticated Levenberg-Marquardt method in place of the simple Gauss-Newton algorithm and by developing robust new methods for obtaining the initial guess in both single and multiple satellite scenarios, the above mentioned difficulties have been overcome. In addition, an expression for the Cramer-Rao lower bound on the error covariance matrix of the extimate is derived.

We also incorporate additional partial information as an extra pseudo-measurement and determine a modified maximum likelihood estimate of the target state and the associated bound on the covariance matrix. In most practical situations, probabilistic models of the target altitude and/or speed at the initial point consistute the most useful additional information.

Monte Carlo simulation studies on some typical scenarios were performed, and the results indicate that the estimation errors are commensurate with the theoretical lower bounds, thus illustrating that the proposed estimators are efficient.

7. BEAM POINTING CONTROL OF A MONOPULSE RADAR FOR MANEUVERING TARGET TRACKING
(E. Daeipour and Yaakov Bar-Shalom, Proc. 1994 American Control Conference)

The tracking of a maneuvering target for the 1994 ACC benchmark problem is considered.

The target is modeled as a hybrid dyanmic system with three modes of operation: the first mode is a nearly constant velocity motion (with a low-level white noise acceleration). In the second model the

target starts/terminates a maneuver (large acceleration increments), while in the third mode of operation it has nearly constant acceleration (the last two modes are Wiener process noise acceleration models).

The tracking algorithm is an Interacting Multiple Model (IMM) approach with three modes corresponding to the three modes of the dynamic system. The evolution of the hybrid system among the modes is modeled as a first order Markov chain. The transition matrix of the Markov chain is designed based on the expected sojourn time in each mode. The covariance of the noise contributing in the evolution of the state in each mode is determined based on the maximum acceleration corresponding to that mode. The results provide a design that yields 3% track loss or less on the benchmark scenarios which include maneuvers up to 7g. Furthermore, an adaptive radar scheduling scheme saves 50% energy and yields better estimates than a Kalman filter.

8. AN INTERACTING MULTIPLE MODEL APPROACH FOR TARGET TRACKING WITH GLINT NOISE
(E. Daeipour and Yaakov Bar-Shalom, Proc. IEEE National Radar Conference, Atlanta, GA, March 1994)

The application of the Interacting Multiple Model (IMM) approach to the problem of target tracking when the radar measurements are perturbed by glint noise is considered. The IMM is a very effective approach when the system has discrete uncertainties in the dynamic or measurement model as well as continuous uncertainties. It is shown that this method performs better than the nonlinear filtering algorithm known as the "score function" method. It is also shown that

the IMM algorithm method performs robustly when the exact prior information on the glint noise is not available, while the score function method requires a more accurate statistical knowledge of the glint phenomenon.

9. IMAGE SEGMENTATION BASED ON OPTIMAL LAYERING FOR PRECISION TRACKING

(Anil Kumar, Yaakov Bar-Shalom and Eliezer Oron, Proc. DIMACS (Discrete Mathematics in Computer Science) Workshop on Optimization, to appear in 1994)

We present a method for precision tracking of a low observable target based on data obtained from imaging sensors. The image is assumed to consist of gray level intensities in each pixel. The intensity range is divided into a target layer and background layers. A binary image is obtained and grouped into clusters using image segmentation techniques. Using the centroid measurements of the clusters, the Probabilistic Data Association Filter (PDAF) is employed for tracking the centroid of the target.

The boundaries of the target layer are optimized by minimizing the Bayes risk. A closed-form analytical expression is obtained for the single frame based centroid measurement noise variance.

The simulation results presented validate both the expression for the measurement noise variance as well as the performance predictions of the proposed tracking method.

The method is first illustrated on a dim synthetic target occupying about 80 pixels within a 64x64 frame in the presence of noisy background which can be stronger than the target. The usefulness of the method for practical applications is demonstrated

for a surveillance problem by considering a sequence of real target images (a moving car) of about 20 pixels in size, in a noisy urban environment.

10. PERFORMABILITY STUDIES OF AMSs WITH MULTIPLE PART TYPES
(N. Viswanadham, Krishna R. Pattipati, and V. Gopalakrishna, Proc. IEEE Robotics and Automation Conference, May 1993)

Automated Manufacturing Systems (AMS) are computer controlled configurations of versatile workstations and autcmated guided vehicles or similar material handling devices. They are highly integrated in terms of both material and information flows In such highly integrated systems, the consequences of failure could be catastrophic. We formulate the notion of performability, a measure of composite performance and dependability for AMS producing multiple part types. We show that the distribution of accumulated performance over a given interval of time, can be obtained by solving a set of forward or adjoint linear hyperbolic partial differential equations.

The performability analysis presented here allows us to compute such useful quantities as the probability of meeting a target mix production, probability that the manufacturing lead time of a part type is less than a given limit. We also conduct analysis using variance and cross covariance functions to evaluate the volume-variety tradeoff.

11. MARKOV-REWARD MODELS AND HYPERBOLIC SYSTEMS
(Krishna R. Pattipati, Ranga Mallubhatla, V. Gopalakrishna, N. Viswanadham, Presented at the 2nd Intn'l Workshop on Performability Modeling of Computer and Communication Systems Le Mont Saint Michel, Franc, June 1993; to appear as a book chapter)

We consider the problem of analyzing event-driven systems that evolve according to any one of a finite set of modes. The mode of evolution is controlled by a random mechanism that switches from one mode to another according to a continuous-time, homogeneous Markov chain. The reward rates in various modes of operation can be different, but are known constants. In this paper, we show that the distribution of accumulated reward over a specified time interval, termed performability, is the solution of a system of either forward or adjoint linear hyperbolic partial differential equations (PDEs). We also show that the moments of performability satisfy a recursive set of ordinary differential equations (ODEs). Our approach provides a unified framework to interpret and extend existing numerical and analytical solutions to the distribution of cumulative operational time and performability, as well as a vehicle to derive asymptotic results, i.e., as the time interval tends to infinity.

12. ESTIMATION AND TRACKING: PRINCIPLES, TECHNIQUES, AND SOFTWARE
(Yaakov Bar-Shalom and Xiao Rong Li, Artech House, 1993

This comprehensive graduate level text presents the engineering tools needed for the design and evaluation of state estimators in stochastic systems.

This book provides ready access to the analytic tools that allow the evaluation of state estimators. It is the first text to provide

guidelines for the selection of estimator design parameters for standard estimators, such as the Kalman filter, as well as the latest multiple model estimators, including the recently developed Interacting Multiple Model algorithm, an ideal estimator for systems with multiple modes of behavior.

Included with this text is the self-contained software DynaEst 2.0, an interactive design tool for Kalman filters and an adaptive multiple model estimator.